On the Importance of Isospin Effects for the Interpretation of Nuclear Collisions

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Abstract. It is demonstrated that many aspects of nuclear collisions, as for instance the evolution of π^+/π^- and K/π ratios with x_F and $\sqrt{s}$, are influenced by isospin effects already present in elementary nucleon–nucleon collisions.

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1 Introduction

The study of heavy ion collisions made at the SPS and the RHIC attracts wide interest. However, it becomes clearly apparent that the understanding of elementary nucleon-nucleon interactions is crucial for the correct interpretation of the more complex nuclear collisions.

One of the basics ingredients to that problem is the role played by the isospin invariance. Since neutrons constitute 60 % of the nucleons inside a heavy ion nucleus, and since even the spatial distribution of protons and neutrons is known to be different in heavy nuclei [5], the proper evaluation of isospin effects in proton and neutron fragmentation is of obvious interest.

The NA49 experiment [1] was the first to measure the yields of identified hadrons from neutron fragmentation in the SPS energy range [2]. In this article, some consequences of these new measurements for relativistic nuclear interactions will be presented.

2 π^+/π^- ratios

The π^+ and π^- yields from both the proton and the neutron fragmentation have been measured by NA49 [2], [3]. As expected from isospin symmetry, the π^+ and the π^- yields change their place when switching from proton to neutron projectiles. Consequently, the ratio π^+/π^- from protons equals π^-/π^+ from neutron fragmentation. These expectations have been verified for a wide range of x_F and for beam momenta of 40 and 160 GeV/c. See the upper panel in fig. 1 for the latter. For details see [3].

It is known that total and differential pion yields in AA collisions differ only little from a linear superposition of nucleon–nucleon collisions according to the number of participant nucleon pairs [4]. It seems therefore reasonable

to predict the evolution of the $(\pi^+/\pi^-)^A$ ratio with the kinematic variables x_F and $\sqrt{s}$ as a function of $(\pi^+/\pi^-)^p$, if the detailed behavior of the latter is known:

$$\left(\frac{\pi^+}{\pi^-}\right)^A (x_F, \sqrt{s}) = \frac{f^p \, (\pi^+/\pi^-)^p + f^n}{f^p + f^n \, (\pi^+/\pi^-)^p} \, (x_f, \sqrt{s}) \quad (1)$$

where f^p and f^n are the relative protonic and neutronic contents of the nuclei – "isospin mixture", $f^p + f^n = 1$.

Evidently, deviations from $(\pi^+/\pi^-)^A = 1$ are predicted, growing with $(\pi^+/\pi^-)^p$. This ratio is both a strong function of x_F and $\sqrt{s}$, see the upper plots on figures 1 and 2.

Whereas the measurements of π^+/π^- dependence on x_F (fig. 1, bottom panel) in the symmetric $SiSi$ system and in central $PbPb$ collisions follow the expectation from the above prediction rather closely, the data indicate a substantially higher neutron content in peripheral $PbPb$ interactions, as has indeed been established with independent experimental methods [5].

There is a steep dependence of the total and the midrapidity π^+/π^- ratios on the $\sqrt{s}$ in pp interactions from pion production threshold to values close to unity at ISR and RHIC energies. The curve represents a parameterization of a large set of existing measurements. Note the midrapidity ratio in the upper panel in fig. 2 (the curve represents a parameterization of a large set of existing measurements), together with the prediction for AA using equation 1.

On the bottom plot, the above prediction is compared with existing measurements in central heavy ion collisions. Again the data (see [7] for the data at lower energies) follow the simple superposition picture rather closely.

3 K/π ratios

Contrary to pions, the charged kaon yields were measured to be the same from both the proton and the neutron pro-
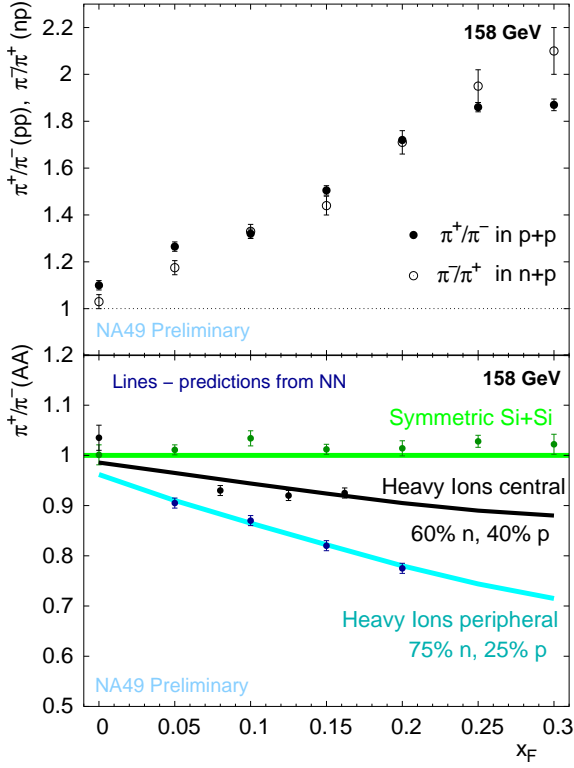

Fig. 1. π^+/π^- ratios in pp, AA and the inverse in np collisions as a function of x_F for different isospin mixtures. NA49 data.

Fig. 2. π^+/π^- ratios in pp and central AA collisions as a function of $\sqrt{s}$ at $x_F = 0$

jectile fragmentation. This experimental observation has important consequences for the K/π ratios in AA collisions. This can be exemplified on the basis of double ratios $(K/\pi)^A/(K/\pi)^p$ as the kaons drop out from the double ratios. Simple relations for K/π ratios from protons and neutrons, equations 2 and 3, and for arbitrary mixtures of these nucleons, equations 4 and 5, can therefore be established:

$$\frac{(K^+/\pi^+)^n}{(K^+/\pi^+)^p} = \frac{(\pi^+)^p}{(\pi^+)^n} = \left(\frac{\pi^+}{\pi^-}\right)^p \tag{2}$$

$$\frac{(K^-/\pi^-)^n}{(K^-/\pi^-)^p} = \frac{(\pi^-)^p}{(\pi^-)^n} = \left(\frac{\pi^-}{\pi^+}\right)^p \tag{3}$$

$$\frac{(K^+/\pi^+)^A}{(K^+/\pi^+)^p} = \frac{(\pi^+/\pi^-)^p}{f^n + f^p (\pi^+/\pi^-)^p} \tag{4}$$

$$\frac{(K^-/\pi^-)^A}{(K^-/\pi^-)^p} = \frac{(\pi^-/\pi^+)^p}{f^n + f^p (\pi^-/\pi^+)^p} \tag{5}$$

Corresponding predictions for K/π ratios assuming a linear superposition as used for the π^+/π^- ratios discussed above, are shown in figure 3. Since there is a strong dependence of the $(\pi^+/\pi^-)^p$ ratio on both $\sqrt{s}$ and on x_F, we can use the double ratios to make predictions for the evolution of the K/π ratios in AA with these kinematic variables. Note the scales below the plot in fig. 3.

The important consequences of the above isospin effects for the interpretation of K/π ratios in AA as a function of x_F have been demonstrated in [2], [3], [6]. It was
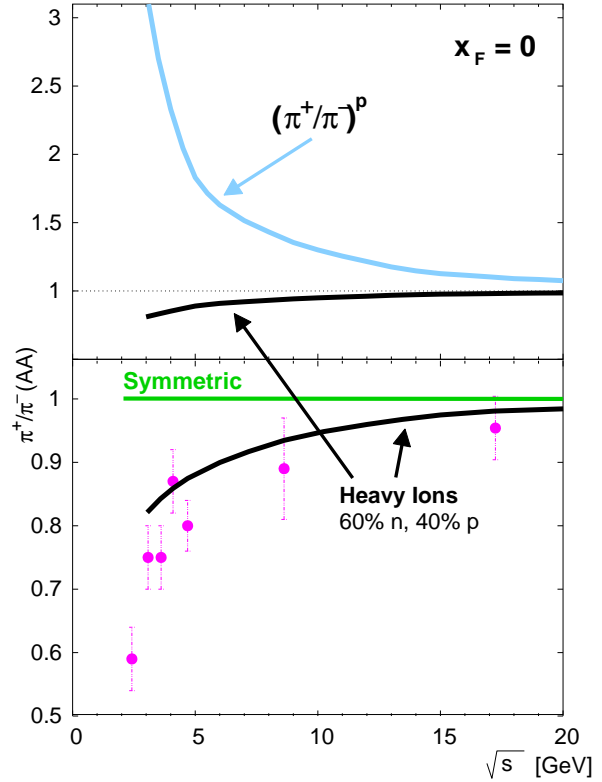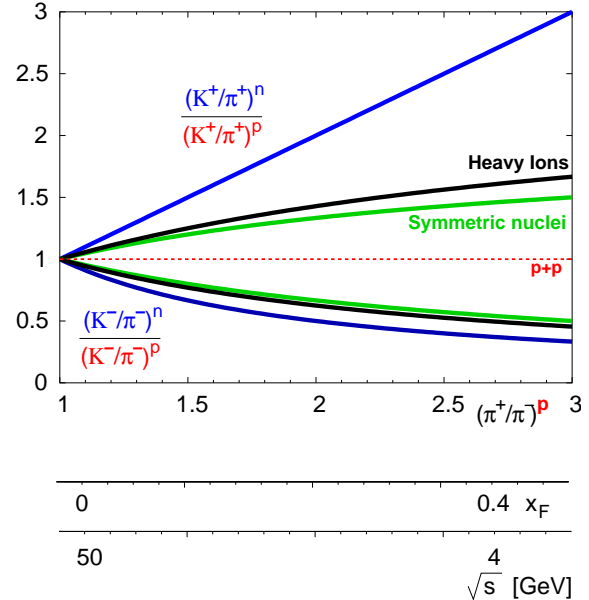

Fig. 3. The evolution of K/π double ratios with x_F and $\sqrt{s}$ for different isospin particle fragmentation.

concluded that the enhancements of strange particles in central pA and AA collisions become comparable once the isospin effects are corrected for.

The evolution of K/π with $\sqrt{s}$ is presented in fig. 4. In the upper panel, the (π^+/π^-) midrapidity ratio from pp collisions is presented. Note the equation 2, and the
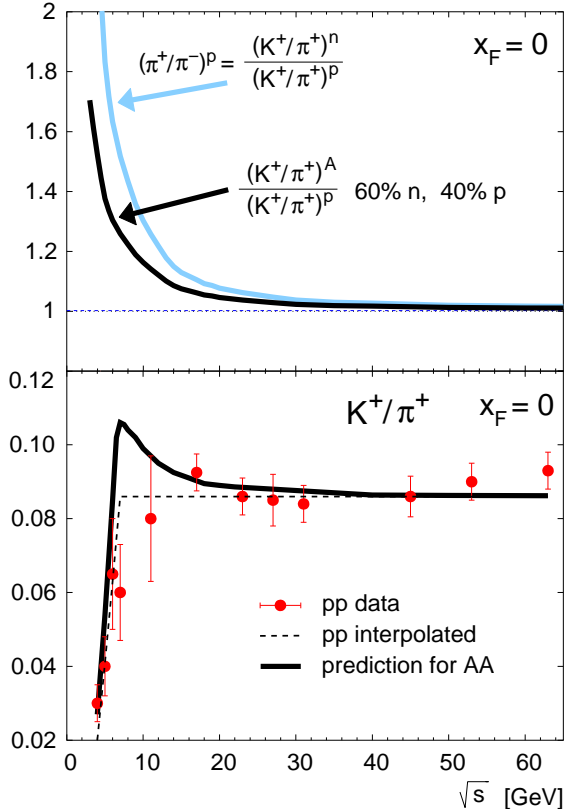
Fig. 4. The evolution of K/π double ratios with $\sqrt{s}$, measured K^+/π^+ midrapidity ratios in pp and prediction for AA.

Fig. 5. Λ/π ratios in pp, Λ/π and prediction for AA.

isospin–mixed one according to equation 4. Existing data are plotted in the bottom panel. They were fitted by a flat line with a threshold.

The isospin correction for positives diverges for decreasing $\sqrt{s}$. This divergence is, however, to be convoluted with the threshold behavior of kaon production. Depending on the detailed $\sqrt{s}$ dependence of the K^+/π^+ ratio in pp collisions, the threshold cut–off tends to produce a spike (fig. 4 lower panel) below about 10 GeV in AA collisions. Such non-monotonic behavior is indeed observed in $PbPb$ interactions [8].

For the negatives, the prediction leads to further depletion below the threshold, changing its slope, as again observed in AA collisions [8].

A similar phenomenon is predicted for the evolution of Λ/π ratios, see figure 5.

4 Conclusions

The fragmentation of neutron and proton projectiles into identified secondary hadrons has been measured at the CERN SPS using np and pp collisions. Based on these measurements and knowledge of π^+/π^- ratio in proton-proton collisions, predictions for AA interactions (assuming that a nuclear collision can be pictured as a sum of independently fragmenting nucleons) have been formulated. The predictions of the evolution of π^+/π^-, K/π and Λ/π, were found to describe the gross features of the data.

This is especially important for strangeness production in the region of $\sqrt{s} < 20$ GeV, where a combination of isospin effects and threshold dependencies creates a pronounced, non–monotonic structure.

Improved datasets (in particular for np interactions) are therefore mandatory before any conclusions on new phenomena in relativistic heavy ion collisions can be drawn.

References

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Top panel:

ratio

K^+/π^+ 60% n, 40% p

K^+/π^+

K^+/π^+ p+p

0

0   10   20   30   40   50   60

$\sqrt{s}$ [GeV]

Bottom panel:

ratio

K^-/π^-

K^-/π^- p+p

K^-/π^- 60% n, 40% p

0

0   10   20   30   40   50   60

$\sqrt{s}$ [GeV]